TD-09-030
December 28, 2009

Design Study of Iron Free Solenoid Magnet for the 4th Detector of ILC

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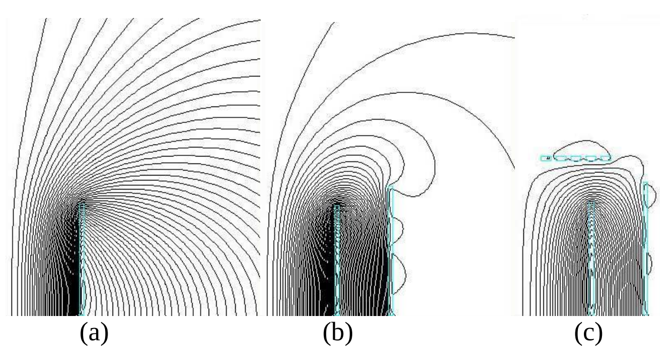
Abstract—**The 4th detector for the ILC does not use an iron yoke, but instead a dual solenoid system to return the flux, eliminate fringe fields, and provide a second tracking field between the solenoids that measures particles after the calorimeter. Iron yoke looses its efficiency at high field beyond 2T. Therefore the elimination of the iron yoke is a natural advancement for the superconducting magnet that makes progress in the direction of high field. Of course every technical detail requires adequate simulation analysis. Assuring field homogeneity and eliminating flux concentration at the end of the inner solenoid is the difficulty of this type of magnet. The scenario for the construction of the 4th detector solenoid described here is just a starting concept. Field calculations to optimize the coil configuration and homogeneity are presented.**

***Index Terms*—ILC, detector solenoid, superconducting, magnet**

I. INTRODUCTION

Uniformly wound thin superconducting coil and iron yoke has been the standard for detector magnets. However, iron saturates at about 2 T and the behavior of the magnetic flux becomes strongly non-linear in a magnet beyond 2 T. The weight of iron is not favored especially when the detector system has to be rolled-in/out. The structure of the 4th detector [1] magnet is different from formerly built detector magnets due to the no-iron construction for field generation of 3.5 T. Flux confinement was confirmed in the early studies [2]. If we just eliminate iron yoke, the solenoid flux spread as shown in Fig. 1 (a). By using another coil, magnetic field is cancelled at large radii as shown in Fig. 1 (b). Addition of another shield coil at the aperture of the solenoid can completely confine the field as shown in Fig. 1 (c). The space in between coils has magnetic field in the opposite direction. This is useful to increase the accuracy of particle momentum analysis.

Although no-iron construction eliminates the problems associated with iron saturation, there are some difficulties to be overcome. Since the aperture of the magnet is opened to air, the magnetic field tends to decline very quickly toward the magnet ends. A special care has to be made to achieve field homogeneity. The stored energy of the magnet is almost doubled due to the return path of the flux. Quench protection is a serious problem for a magnet with large stored energy. Due to the turning of the flux, magnetic field at the ends of inner coil becomes very high. Early design trial using simple dual solenoid coil showed a very non-uniform filed in the detector area, and very high field at the inner coil edge exceeding 10 T [3]. The field uniformity can be improved by having more current at the ends. Mikhailchenko achieved ±0.1% field homogeneity in the required 2mϕ x 3m space with an improved design[4].



(a) (b) (c)

Fig. 1. Confinement of the Magnetic Flux.
Solenoid field (a), can be confined by the return path outer coil (b), and shield coil at the aperture (c).

Spacers at the end part was found effective[5]. However the peak field at the end was still too high to have such high current density. The key issues in this design study are bringing down the peak field, achieving field homogeneity, and reducing the stored energy of the magnet.

II. Magnetic Field Design

A. Notch Solenoid

One apparent way of field improvement is to make notches at the ends. The notch thickness of the coil also helps to reduce the peak field. An example of a notch solenoid is shown in Fig. 2. The flux is confined in the magnet and the field homogeneity satisfies the requirement but the peak field of 7.8 T is still too high for NbTi conductor with indirect cooling. Since large notches are an obstacle for the detector installation, the radius of the coil has to be increased.

B. Sectioned Solenoid

Dividing coils into blocks gives degree of freedom to adjust the field uniformity. An example of optimized result is shown in the coil geometry of Fig. 3. This design quoted in the 4th detector LOI achieves good field and not too high peak field. The peak field of 5.0T is low enough to avoid the use of compound superconducting materials. Compound materials are expensive and mechanically weak. The magnetic flux is confined by the outer coils and the end shield coils to eliminate the leakage field. The ± 0.1% good field region is 6.0 mϕ x 4.8 m. Such good field is actually over-specification but the physical accessibility for the detector installation needs this coil.

The overall current density in the coil is 18 A/mm^2 that is about the same level used for CMS magnet and not difficult to carry for a standard Nb-Ti superconducting cable. The total stored energy of the whole solenoid system is 5.08 GJ. The total Inductance is 25.4 Henries, if the magnet is operated at the 20kA current. These numbers are larger than any previously constructed detector solenoid magnets.

III. Coil Construction

Conductors in the inner coil receive large electromagnetic forces in both radial and axial directions. The axial forces are especially large compared to previously built magnets due to the turn around of the flux. If the magnet winding is divided into many coils, it is not appropriate to use usual solenoid winding because there are too many ends. The problem of the solenoid winding is the

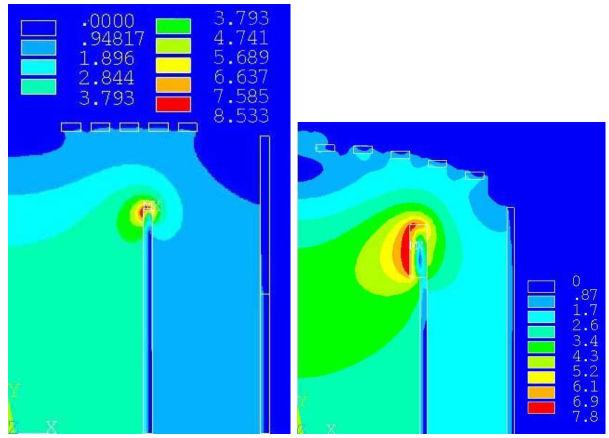


Fig. 2 Solenoid coil with notches and high current density at end. End high current improves homogeneity but peak field become large. Notch coil at the end helps to improve the field homogeneity and suppresses the concentration of the flux at the edge.

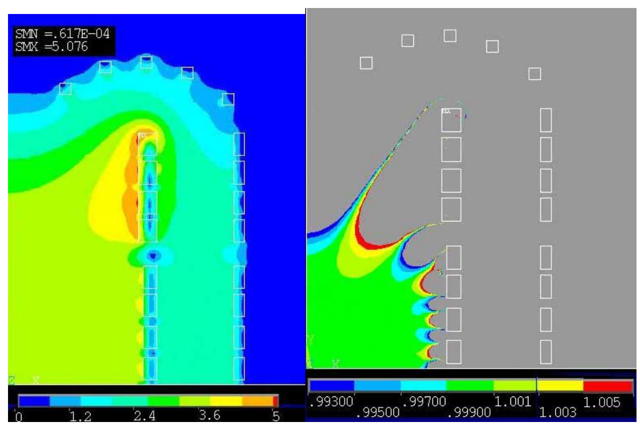


Fig. 3 Sectioned Solenoid with notches
By sectioning the solenoid coil, the fine adjustment of the magnetic field can achieve a large ±0.1% good field region without increasing the peak field. Left shows the peak field. Right is the contour map at every 0.2% field.

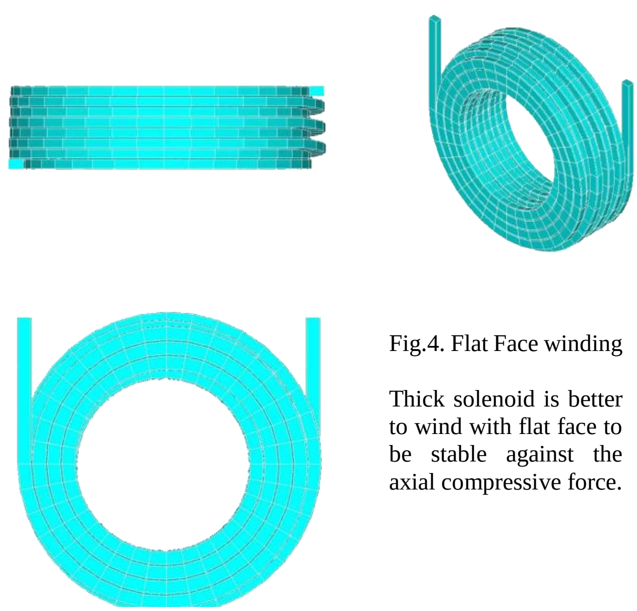


Fig.4. Flat Face winding

Thick solenoid is better to wind with flat face to be stable against the axial compressive force.

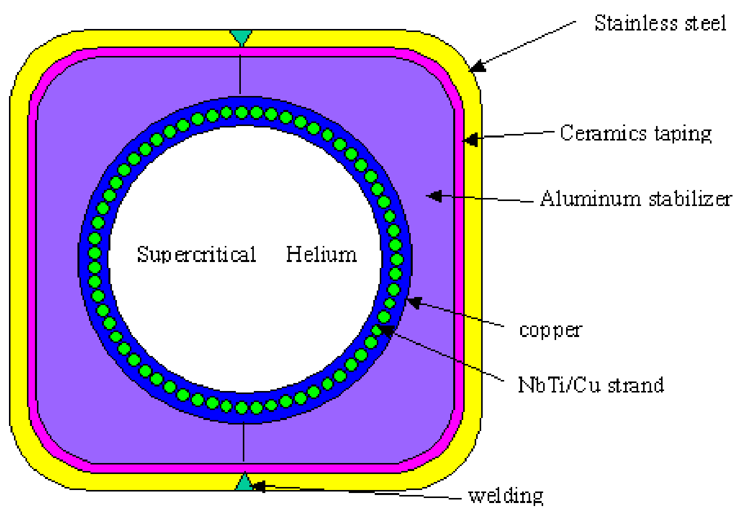


Fig. 5. Conductor Cross Section

layer-to-layer transition at the ends. The conductor has to go up to the next layer at the end in a multi-layer solenoid. This transition makes end structure complicated. Since a large axial force works on the coil, interface between coil and flange had better not have a bump or hump to avoid the stress concentration. Small gaps often cause conductor motion that triggers the quench of the magnet. We could introduce spacers with complicated shapes but the magnet is divided into many blocks of coils and each coils has two ends.

A. Winding method

A solution for this problem is to use flat face winding shown in Fig. 4. It is possible to make flat face at the end if we wind the coil from out-to-in and then out-to-in. It requires a more complicated winding machine than a usual solenoid winding. Since we are going to make 16 similar coils, investment in a winding machine is worthwhile. The layers in this winding are formed in the axial instead of the radial direction. The transitions between layers are made at the innermost turn and outermost turn. The interface between the coil and bobbin is not flat but we do not have inner bobbin because the hoop stress is in the outward direction. Outer bobbin may need a groove for the transition turn but it is much simpler than that of usual solenoid ends. If the conductor is strong enough, there is no need for the outer bobbin either.

B. Conductor

An idea for a strong conductor cross section is shown in Fig. 5. The conductor is made of usual Nb-Ti/Cu compound strands. Probably 128 strands are woven on a pipe and covered by another pipe. The conductor and the pipes are tightly connected by the expansion of the inner pipe. This technology was established in the VLHC low field ring study (Pipetron). The aluminum stabilizer covers over it. The outermost layer of the conductor is stainless steel but the ceramic insulator is inserted between the cover and stabilizer. The stainless steel cover provides the strength of the conductor. Another advantage of this conductor is in the cooling. Super-critical helium flow in the pipe ensures the cooling of the superconductor even when there is a severe heat load from the support structure of the coil.

C. Internal Cooled conductor with armor and insulation is an idea for the conductor

The superconductor is directly facing the helium flow. The thermal resistivity of the ceramics even helps to reduce the conductor temperature. It is noted that the thermal resistance of the insulator is a large problem for the cooling in the usual conductors that is cooled from outside. Since the electrical insulation is in the conductor, we do not worry about the insulation between turns during the winding. We can even weld the conductor for mechanical purposes

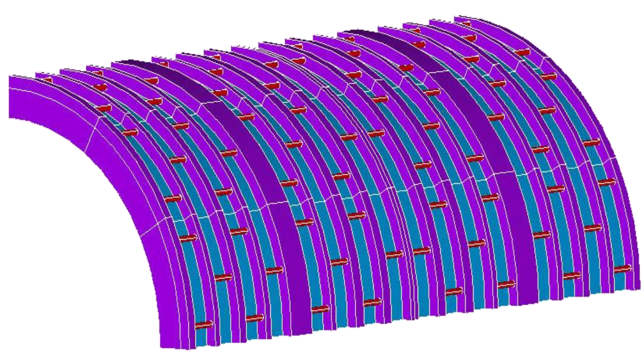


Fig. 6. Mechanical Support with No-Bobbin Structure

We need development of such conductors, since this technology should be beneficial for future superconducting magnets of all applications. The materials for this conductor are very conventional and thus cost saving compared to new high strength aluminum alloys.

D. Support

If we use this conductor, the conductor is strong enough to sustain hoop stress. We do not need any bobbin or support cylinder structure. The structure of the magnet becomes very simple and yet there is advantage in the application of the axial pre-loading

Since the axial stress is large in this dual solenoid system, it is desired to have axial pre-compression in the coil so that the conductor will not have motion during excitation. It is very difficult to apply pre-compression to the coil if a bobbin exists. Friction between coil and bobbin will prevent axial preloading. With no bobbin structure, axial pre-loading can be applied by having a force between spacers by high strength Ti-alloy (Inconel) rods. The assembly view of the magnet is shown in Fig. 6. The magnet coils are assembled with the spacers and the connecting rods.

The problem of this design is the total length of the magnet system. Total length is 17 m and this is necessary to have good field region wide enough. A large portion of the flux is not efficiently used for particle analysis. The inner diameter of the coil has to be physically large because of the notch thickness to maintain accessibility for detector installation. As a result, the weight of the magnet system will not be light enough for easy roll-in/roll-out. The stored energy of over 5 GJ is large enough to cause problems. Quench protection system for such large stored energy is not easy. Time constant to discharge current is very long and yet quench propagation through conductor joint is not fast. Divided protection system may be necessary to protect the magnet from burn-out. Active heater system to force the entire magnet to become normal on quench detection is also useful but this has to be designed to work even when the electricity fails.

It is inevitable to have current at small radius to keep magnet size in a reasonable range. On the other hand, accessibility to the magnetic volume requires a certain aperture. This is the reason for the large size of the magnet.

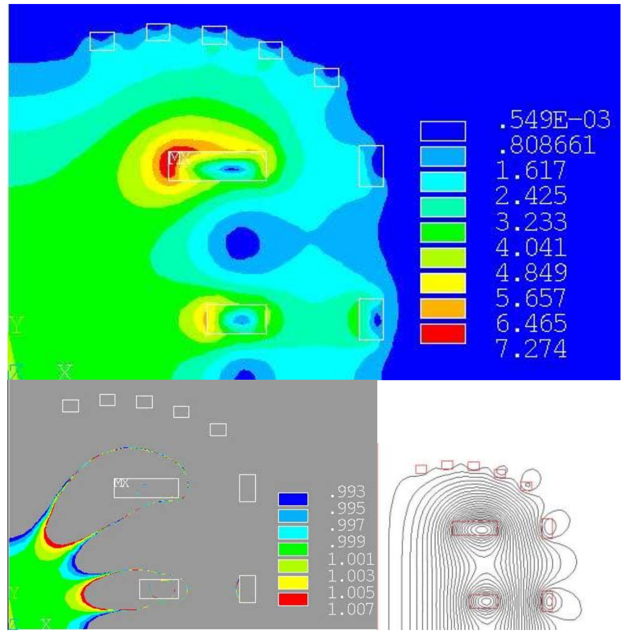


Fig. 7. Two Block Double Helmholtz Coil Design. Top is the field distribution. The bottom left is the field map to show the good field region by the contours at every 0.2 %. The bottom right is the flux pattern of the magnet.

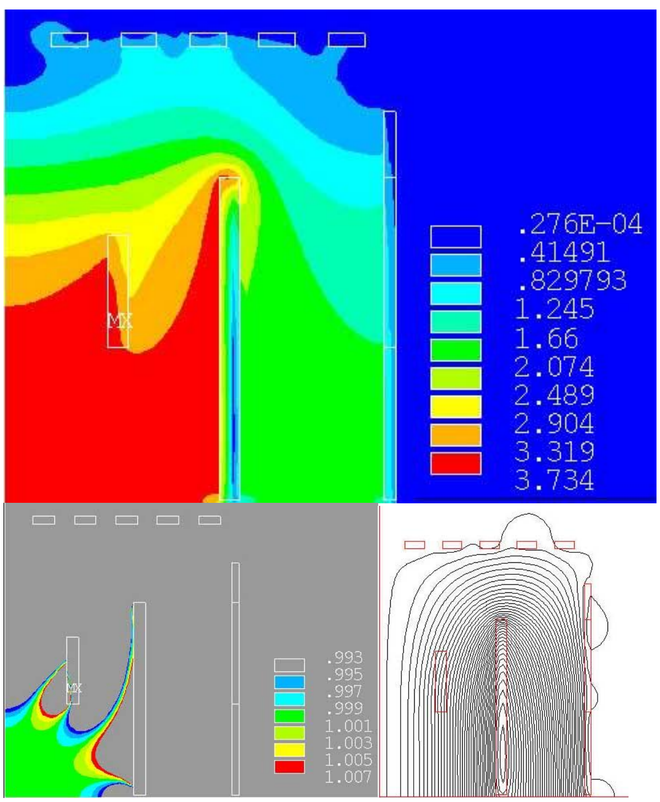


Fig. 8. Two Block Double Helmholtz Coil Design.
Top is the field distribution. The bottom left is the field map to show the good field region by the contours at every 0.2 %. The bottom right is the flux pattern of the magnet.

IV. Alternative Designs

If the end part of the coil can be placed after installing the detectors, a lot of extra space is eliminated. There are possibilities for alternative designs assuming a change of the installation procedure. One of the simple and efficient coil configurations with fewer conductors is shown in Fig. 7. This magnet uses only 2 blocks of coils. The shape of the coil is not a simple thin solenoid but a set of thick ring coil blocks that might better be called multiple Helmholtz coils. Certainly, re-arrangement of outer detectors is necessary to use this type of magnet. This magnet is made with 4 cryostats. Each cryostat is a combination of inner and outer coil. Detectors are maintained by moving these cryostats on a rail. The ± 1 % good field region of this magnet is 2.54 mϕ x 3.60 m. The stored energy is 4.34 GJ. But the inner edge of the inner end coil receives the highest field of 7.3 T. This field is within the range of NbTi conductor with 20 A/mm^2 current density.

If an extra correction coil is allowed at smaller radius, the magnetic field can be better. It requires the rearrangement of the end cap detector space. Figure 8 shows the field deviation of such a magnet. A 3.0 m x 3.0 mϕ area is in the $\pm$ 0.1 % deviation range. All the flux is confined in the vicinity of the magnet. The peak field in this design is as low as 3.7 T. The highest field is at the correction solenoid but the current density of the correction coil is just 17% of that of the inner coil, i.e., 2.5 A/mm^2. This coil has to be removed at every detector maintenance, but very unlikely to make quench or it could be made of a water cooled normal conductor. The current density in the inner coil is 15.5 A/mm^2, much lower than that of CMS. The stored energy for the whole system is 2.58 GJ. Correction coil receives 1900 tons electro-magnetic force to be pushed out but this is manageable by the support system. The length of the magnet system including shield coils is 15 m. A good thing of this design is the applicability of technologies developed in CMS. Inner coil can be very close to the CMS coil with less field and less current. The conductor can be aluminum alloy stabilized Nb-Ti. The support system can also be the same as that of CMS.

V. Electro Magnetic Force

The electro-magnetic force can be calculated based on the field distribution and the current. However, calculation error becomes large when magnetic field rapidly changes at the point where the current is located. On the other hand, calculation of total magnetic energy for the imaginary motion of the coil can directly give force on the coil. The stored energy is:

$$U = \frac{1}{2} L I^2 \qquad (1)$$

then, the force in the direction of geometry change x is:

$$F = -\frac{dU}{dx} = -\frac{1}{2}\frac{\partial L}{\partial x} I^2 - L I \frac{\partial I}{\partial x} \qquad (2)$$

Applying the flux conservation condition:

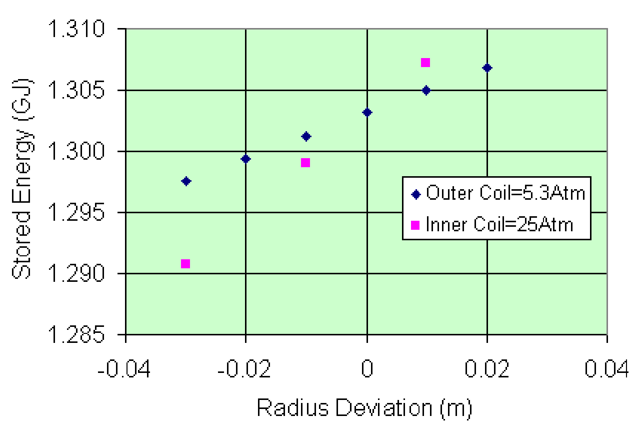
$$\frac{d\phi}{dx} = \frac{\partial L}{\partial x} I + L \frac{\partial I}{\partial x} = 0 \qquad (3)$$

Then, the force is:

$$F = \frac{1}{2}\frac{\partial L I^2}{\partial x} = \frac{\partial U}{\partial x} \qquad (4)$$

The stored energy can be calculated as the sum of B^2 of all the elements. Careful meshing is necessary for this calculation because the stored energy is very much mesh dependent. It sometimes creates jumps of energy due to a change in meshing. The force calculation of this study was made using the gradient of the energy as the force to move the coil in this direction. The hoop stress is less than usual 3.5 T magnet because the outside of the inner coil has magnetic field in the opposite direction.

The largest force in this magnet is the axial stress in the mid plane. Therefore, dividing the solenoid into pieces and supporting each portion is preferred. However, large axial stress is a compressive force. The axial stress in the outer



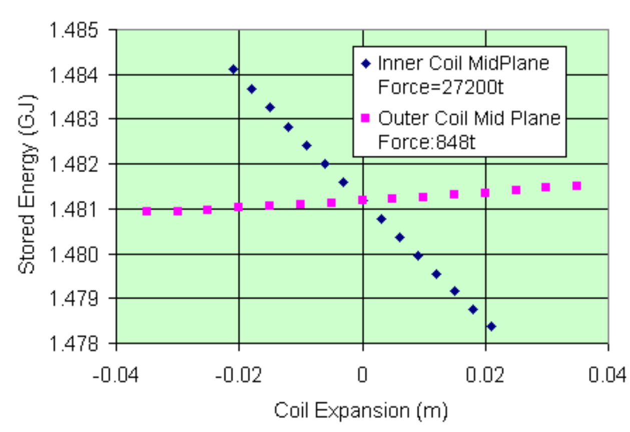


Fig.9 Hoop Stress (left) and Axial Stress (right)
Electromagnetic force is given by the gradient of the total stored energy Stored energy is plotted for half model. Starting point of coil motion varies by the fine tuning of the coil position. These are some of the typical results.

coil is a tension but not very large. Positioning force also works in this magnet. The shield coil is pushed out by the force of 1900 t to5800 t depending the space to the solenoid coils. If the magnetic field is confined in a smaller space the push-out force naturally become large. The third solenoid coil is pushed out by the force of 4200 t. These push-out forces have to be supported by the coil support in the cryostat. The cryogenic design of the support with minimum heat load is required. The position of the inner coil is essentially re-centering. The position of the inner coil is kept at the center of the outer coil by itself. However, due to the adjusting gap at he mid plane, the axial stable point is split into two positions. So it is unstable at the very center. The de-centering force in this case is 0.53 t/m, which is very small compared to other forces.

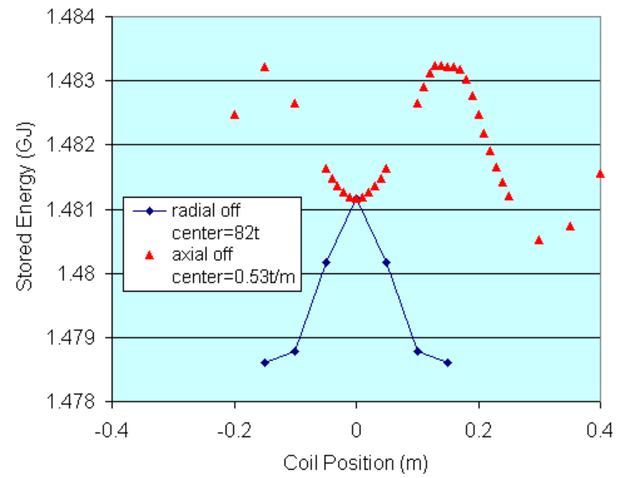


Fig.10. The Stored Energy against The Position of Inner coil
Up concave and down concave are the stable and unstable balancing point, respectively.

In summary, it can be said that the support of the main coils are almost limited to just supporting the weight in dual solenoid magnet. The very large Electro-magnetic force works on the shield coils and end coils. The temperature-rise in these coils is not critical because both magnetic field and current density are low in these coils.

VI. Quench Protection

The magnetic field homogeneity and electro-magnetic forces in the dual solenoid magnet is manageable. Dividing the inner coil into pieces is a good idea from the viewpoint of internal stress reduction. But the quench protection becomes more complicated. The quench protection in such a large magnet is not easy. First extraction of the stored energy is not applicable because of a very long time constant due to the large inductance. Quench propagation across segments is not straightforward. It might stop propagation at the connection depending on conditions. In such a case the current has to be by-passed to the next coil. However, to avoid the force imbalance, these switching circuits have to be made symmetrically. In case of three-coil configuration with no divisions in the coil, propagation property of aluminum conductor is enough to protect the coil as shown in the achievement of CMS magnet..

Conclusion

4th detector magnet design is possible with no iron structure. It can have a large enough good field region in a compact body. The highest field on the conductor is well in the range of Nb-Ti alloy conductors. Stored energy and the required current density is in the range of CMS. Detailed technologies for this magnet can just be an extension of the established technology of the CMS magnet.

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